10-Gb/s transmission over 20-km single fiber link using 1-GHz RSOA by discrete multitone with multiple access

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Abstract: We demonstrate a novel 10.5-Gbit/s transmission scheme over 20-km single fiber link by using a remotely fed 1-GHz reflective semiconductor optical amplifier (RSOA). Discrete multitone (DMT) modulation with adaptive bit-/power-loading is applied to overcome the bandwidth limitation of the RSOA. Transmission performance of the proposed scheme is analyzed in terms of various system parameters, such as the nonlinearity of the RSOA, optical signal-to-noise ratio of the optical seed carrier, the overhead size impact on dispersion, the number of DMT subcarriers, and the reflection noise from the single fiber link. We also report flexible-bandwidth-allocated multiple access operation based on the proposed scheme. The throughput for all cases is approximately 10 Gbit/s with BER < 10^{-3}.

OCIS codes: (060.2330) Fiber optics communications; (060.2360) Fiber optics links and subsystems; (060.4080) Modulation.

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1. Introduction

Wavelength division multiplexed passive optical network (WDM PON) is a strong candidate for next-generation optical access networks due to various advantages such as a large bandwidth supported by individual optical carriers, transparency to data format, and robust security, ease of upgrading and maintenance [1–4]. Unfortunately, most service providers are reluctant to realize WDM PON because it requires new and often costly investments. For example, replacing power splitters with WDM filters in the outside fiber plant is not straightforward for existing time division multiplexed passive optical networks (TDM PONs). Putting new optical transceivers in the optical network units (ONUs) is more cumbersome than in the optical line terminals (OLTs) because they have to be implemented at the subscriber's premises and hence, the subscriber bears the implementation costs. Therefore, recent studies on WDM PON have focused on improving the cost-effectiveness of the transceivers at the ONUs [5–7].

A colorless ONU is an inevitable solution required to relax the inventory costs of WDM PON because the same transceiver can be used for any ONU regardless of the wavelength channel [8–11]. It has been widely recognized that a reflective semiconductor optical amplifier (RSOA) is one of the most promising components for realizing colorless ONUs because of the wavelength-agnostic and modulation performance within C-band wavelengths. Therefore, individual optical sources at the ONUs are not required [12–17]. Since most commercially available RSOAs are bandwidth-limited to around 1 GHz, they are not suitable for the next-generation optical access network, which is based on 10-G PONs.

Several techniques have been recently investigated to overcome the bandwidth limitation of the RSOA [18–35]. They consist of four categories: electrical equalization [19–27], optical filter detuning [24–29], specifically designed RSOA modules and driving circuits [23,30–33], and employing optical orthogonal frequency division multiplexing (OFDM) and its baseband version, discrete multitone (DMT) techniques [34,35].

Electrical equalization techniques are commonly used to solve the bandwidth limitation. By employing multi-tap electrical equalizers at the OLT, digital-to-analog converters (DACs) are avoided to simplify the ONU. On the other hand, since the electrical equalization is based on a single carrier transmission system it can lead to significant frequency chirping when directly modulating the RSOA. Therefore, it needs to be carefully tuned to chromatic dispersion.

In addition, several equalization techniques applied to RSOAs have been demonstrated in an optical back-to-back or in a dual-fiber link, where the RSOA is separately fed by a continuous wave (CW) light source locally or through a separate fiber. These implementations are fairly costly for realistic implementations.

Some techniques have proposed specially designed RSOA package and driving circuits to minimize the use of complex signal processing [30,33]. However, complicated fabrication and integration steps are required with respect to commercially available RSOAs.

Recently, advanced and spectrally efficient modulation techniques such as OFDM and DMT have been widely used for bandwidth limited systems, such as digital subscriber line (xDSL), power line communications and plastic optical fiber systems [36]. With respect to RSOA, 7.5-Gbit/s was demonstrated for a locally fed 1-GHz RSOA using OFDM [35].

In this paper, we focus on a single fiber 20-km link with reflection noise in which 1-GHz RSOAs are remotely fed from the OLT. In addition, we use the bit-/power-loading algorithm [37,38], in combination with quadrature amplitude modulation (QAM), to maximize the link capacity and to allow multiple ONUs to transmit upstream data using the same wavelength. Experimental proof-of-concept setup with two ONUs demonstrates symmetrical and asymmetrical bandwidth allocation. The performance was analyzed in terms of the nonlinearity of the RSOA, optical signal-to-noise ratio (SNR) of the optical seed carrier, the cyclic prefix size effect on the dispersion, the number of DMT subcarriers, and the reflection noise from the single fiber link. The achieved throughput was > 10 Gbit/s with BER<10^{-3}.

2. Proof of concept of the proposed scheme

Figure 1 shows the proposed scheme for the flexible bandwidth allocation of DMT-based multiple access in case of two ONUs. An OLT provides multiple CW wavelength channels to each ONU. After the demultiplexer, one of these CW wavelength channels becomes a common optical seed carrier with the wavelength of λ_k to ONU 1 and 2. This seed signal is transmitted through a standard single mode fiber (SMF) link and distributed to each ONU by a power splitter. For each distribution, the seed signal is injected into the RSOA and modulated for the upstream transmission. At this point, the signal is allocated to a certain number of DMT subcarriers according to the designated ONU as described by the inset of the mapping scheme in Fig. 1, filled by dashed line. Some of the DMT subcarriers are zero-padded as a guard band to minimize the interference between the two ONUs. The modulated upstream signal from each ONU is combined and retransmitted through the same SMF link and recovered at the OLT according to the designated DMT subcarrier allocated to that ONU. The subcarrier allocation scheme is implemented digitally in the frequency domain. Flexible bandwidth allocation for multiple access can be achieved by modifying the ratio of the occupied DMT subcarriers for the ONUs. Under the proposed multiple access scheme, it is critical that optical beat noise and strict time synchronization problems are avoided for ONUs sharing the same wavelength.

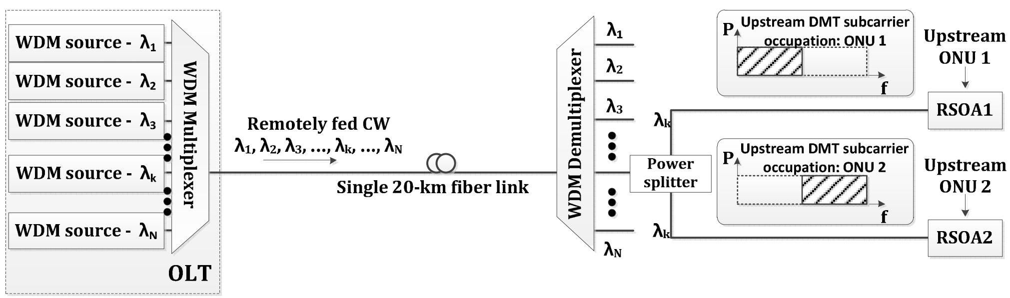

Fig. 1. Operational principle of the proposed scheme for multiple access with wavelength sharing.

3. Experimental setup

The experimental setup of the proposed scheme is shown is Fig. 2. A CW optical source in the OLT was realized by a tunable light source (TLS) at 1550 nm with an output optical power of 5.8 dBm in order to provide a CW optical seed carrier to the RSOA. This optical power was launched into a 20-km standard SMF link through optical circulator (OC) 1. OC 2 and OC 3 were used to separate and monitor the input optical power of the RSOA without affecting the RSOA output. Due to the polarization dependent loss of the RSOA, a polarization controller (PC) was used to optimize the input polarization state. The RSOA was operated with a bias current and a temperature of 50 mA and 20 °C, respectively. In this condition, the measured −3-dB modulation bandwidth of the RSOA was limited to less than 1 GHz as shown in the inset of Fig. 2.

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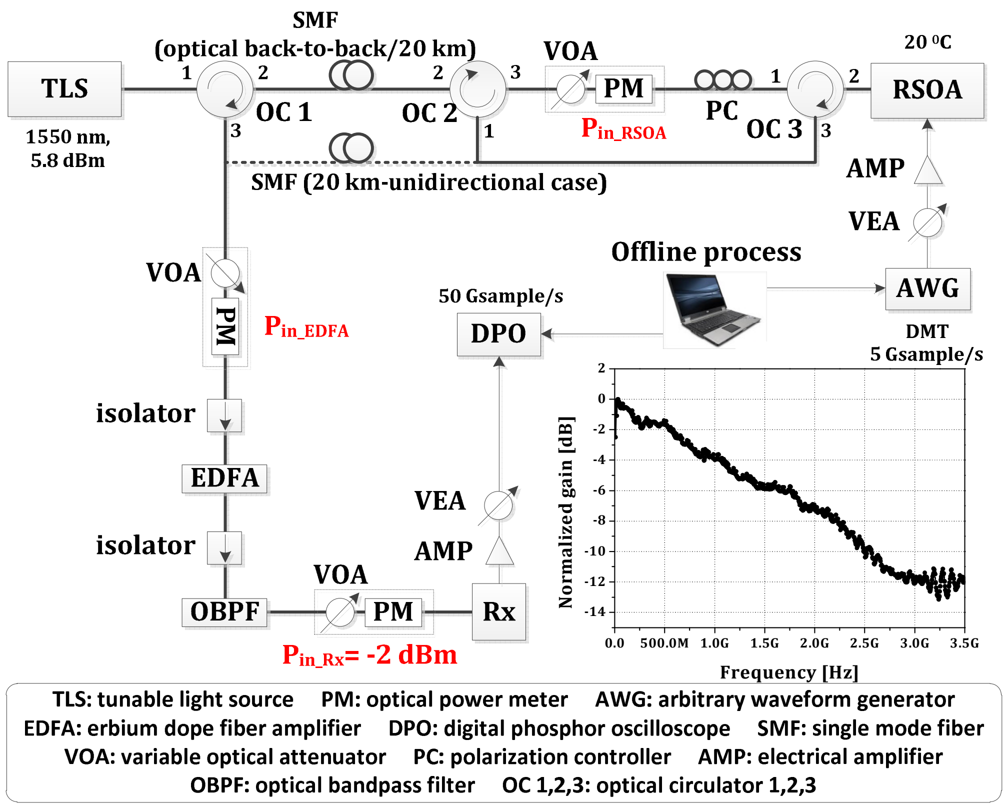

Fig. 2. Experimental setup (inset: frequency response of the RSOA operated at a bias current of 50 mA, the input RSOA optical power of 0 dBm).

The adaptively loaded DMT signal was generated by MATLAB®. The number of DMT subcarriers was 512, ranging from DC to 2.5 GHz, and the fast Fourier transform (FFT) size was 1024 according to Hermitian symmetry. An arbitrary waveform generator (AWG: Tektronix 7122B) sampling at 5 GS/s was employed to modulate the RSOA. For full modulation amplitude, the magnitude of the DMT signal from the AWG was optimized using a variable electrical attenuator (VEA) and an electrical amplifier.

The DMT-encoded optical signal from the RSOA was reflected back over the same 20-km SMF link. After passing through OC 1, this signal was delivered to a preamplifier, realized by an erbium doped fiber amplifier (EDFA) and optical isolators. Using an optical power meter (PM), the input optical power of the preamplifier was also monitored. In order to minimize amplified spontaneous emission (ASE) noise, an optical bandpass filter (OBPF) with the center wavelength of 1550 nm was used after the preamplifier. The input optical power of an optical receiver (HP 11982A) was also monitored. At this point, its input optical power was maintained at −2 dBm. The optical receiver had a −3 dB electrical bandwidth of 11 GHz. The received DMT signal was captured by a digital phosphor oscilloscope (DPO: Tektronix 72004B) with sampling speed of 50 GS/s. Finally, it was processed and evaluated offline in MATLAB®.

4. Results and discussions

In order to apply the adaptive bit-/power-loading algorithm, it was essential to estimate the channel SNR for every DMT subcarrier. A probe signal, employing the same level modulation of 16 QAM and uniform power allocation to each subcarrier, was firstly transmitted before starting the loading algorithm. Figure 3 (a) and (b) presents; the measured error vector magnitude (EVM) traces of the probe signal, the adaptively loaded number of bits

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and power profile according to the channel SNR, and the bit error rate (BER) performance per each DMT subcarrier in the optical back-to-back and the 20-km single fiber link transmission, respectively. It was verified that indeed more bits were allocated to the subcarrier with lower EVM (higher SNR) and less bits were allocated to the subcarrier that had higher EVM (lower SNR). The channel power was loaded to each subcarrier according to the SNR characteristics for the given modulation format in order to optimize the performance.

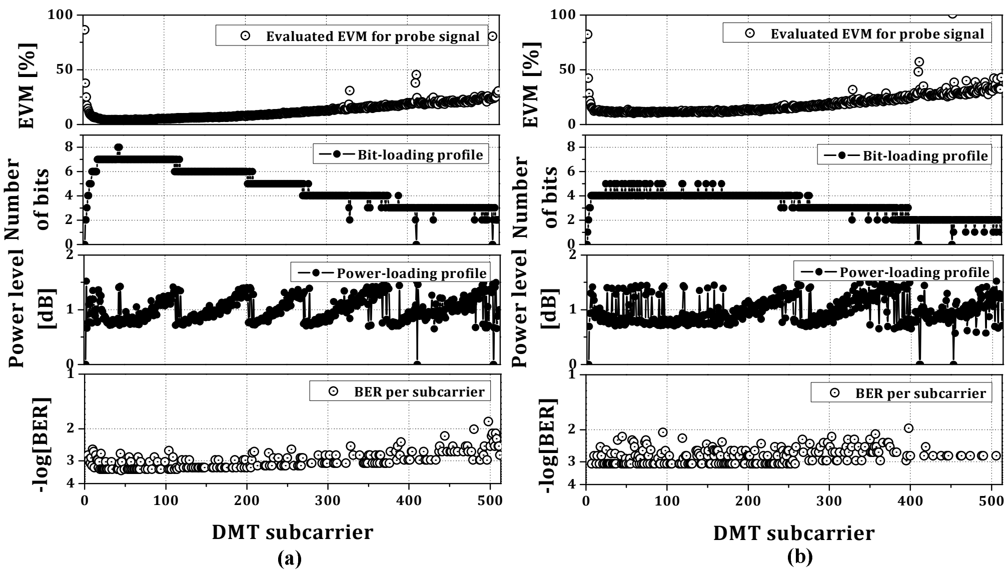

Fig. 3. Probe EVM, bit-/power-loading profile and its BER performance per each subcarrier for (a) the optical back-to-back and (b) the 20-km single fiber link.

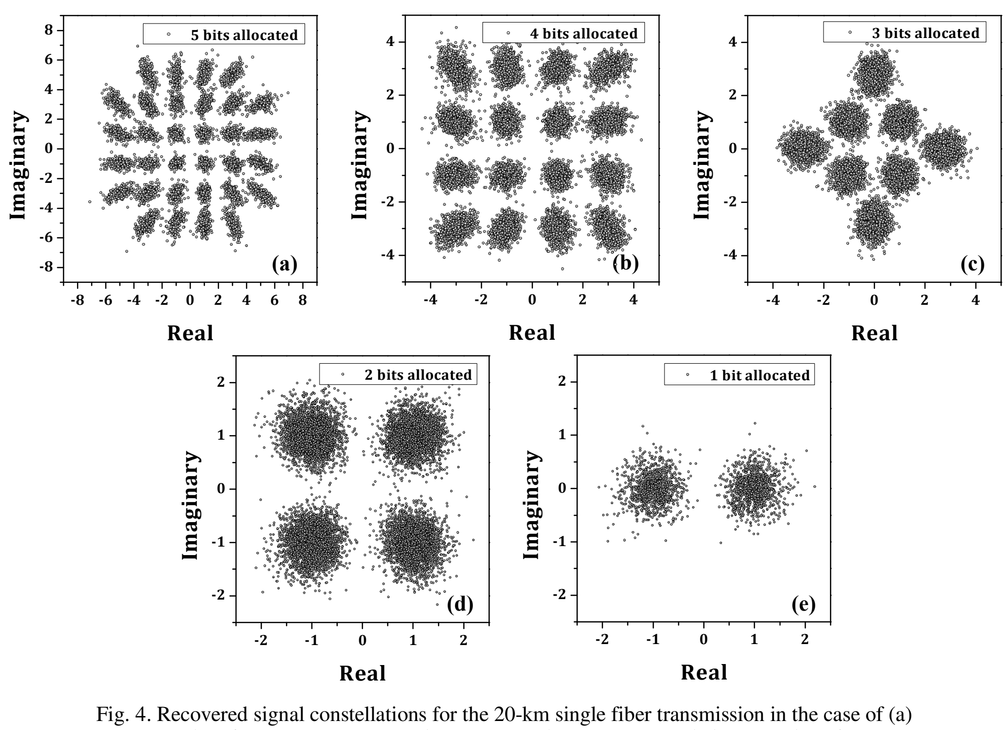

Fig. 4. Recovered signal constellations for the 20-km single fiber transmission in the case of (a) 32-QAM, (b) 16-QAM, (c) 8-QAM, (d) 4-QAM, and (e) BPSK-encoded DMT subcarriers.

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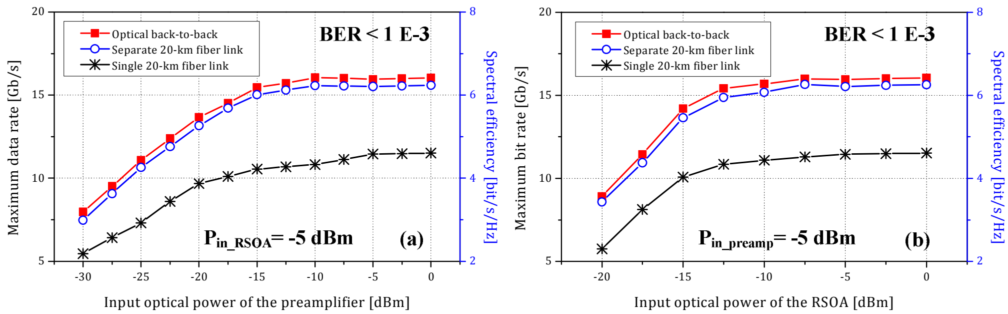

Fig. 5. Maximum achievable data rate of the proposed scheme as a function of (a) the input optical power of the preamplifier and (b) the input optical power of the RSOA.

As represented in the evaluated EVM of the probe signal, the channel SNR of the 20-km single fiber link was worse than that of the optical back-to-back. Consequently, the maximum number of bits, allocated on a DMT subcarrier, was 5 (equivalent to 32-QAM). It was smaller than the case of the optical back-to-back (8 bits allocation, equivalent to 256-QAM). It resulted in a penalty in terms of maximum achievable data rate as described in Fig. 5. The maximum data rate achieved in the optical back-to-back case was around 15 Gbit/s, which means a degradation of 5-Gbit/s throughput, introduced by the 20-km fiber link. The most critical reason for this degradation was the reflection noise from the single fiber transmission. According to the performance in a 20-km separate fiber link in Fig. 5 (based on the dashed line link setup in Fig. 2), this penalty could be suppressed to less than 0.5 Gbit/s because the modulated DMT signal from the RSOA was separated from the optical seed carrier, and consequently, a reduction of the reflection noise. Nevertheless, it was possible to achieve 10.5 Gbit/s transmission (equivalent to a spectral efficiency higher than 4 bit/s/Hz) with an average BER lower than 10^{-3} (9.89×10^{-4}) for the 20-km single fiber link, when both optical powers before the preamplifier and the RSOA were higher than −15 dBm. Good signal constellations could be achieved as shown in Fig. 4. Note that the RSOA was operated with saturated gain. However, it was verified that the maximum achievable data rate was not degraded as represented in Fig. 5 (the threshold input optical power of the RSOA for the gain saturation was −20 dBm). Therefore, the proposed scheme was relatively robust to nonlinear signal distortion from the gain saturation. The optical SNR of the seed carrier, represented in terms of the input optical power of the RSOA, was a dominant factor to affect the performance.

The proposed scheme could be sensitive to the system parameters, such as the number of DMT subcarriers, the magnitude of the modulating DMT signal, and the overhead size including the cyclic prefix. There was a small performance improvement observed when the number of DMT subcarriers increased, as the available bandwidth is fragmented into more subchannels. Nonetheless, its enhancement (about 1 Gbit/s) was negligible with respect to the maximum achievable data rate as shown in Fig. 6 (a) and (b). The evaluated channel characteristic of the proposed scheme, mostly based on the SMF link, was almost flat.

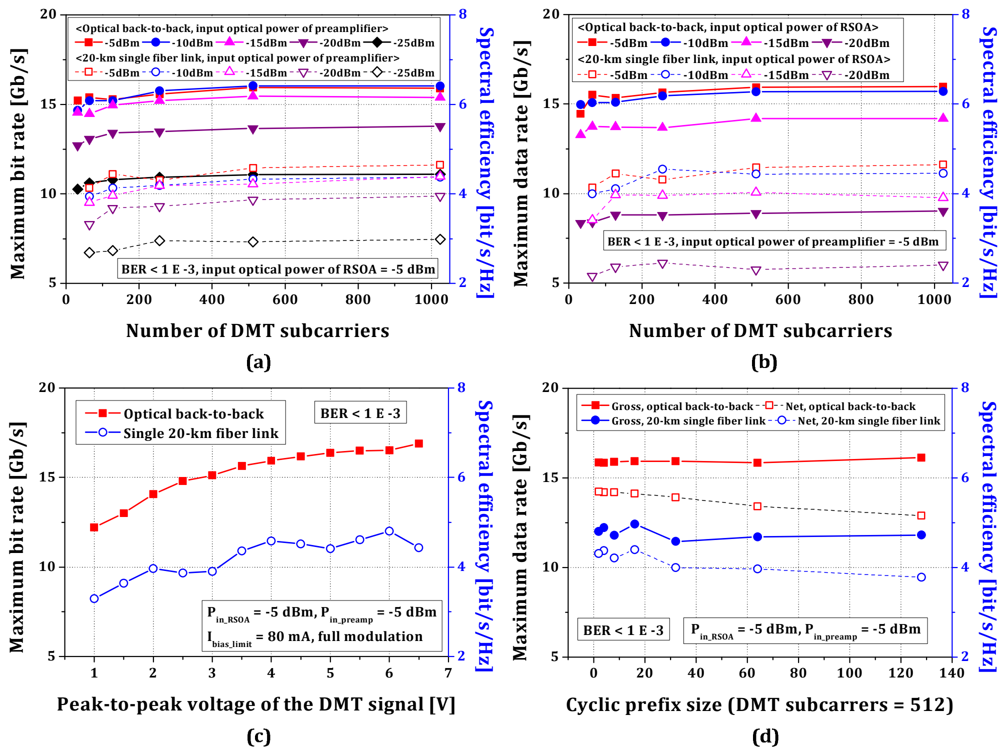

Fig. 6. Performance analyses of the proposed scheme as a function of; the number of DMT subcarriers with (a) the input optical power of the preamplifier, (b) the input optical power of the RSOA; (c) the magnitude of the modulating DMT signal, and (d) the cyclic prefix.

The performance was analyzed in terms of the DMT magnitude to estimate the nonlinear modulation effect of the RSOA. For experimental consistency, modulation index of the DMT signal was maintained at 1 ("full modulation"). As described in Fig. 6 (c), the maximum achievable data rate was improved when increasing the DMT magnitude because the optical SNR of the modulated signal from the RSOA was proportional to the DMT magnitude as well as to the input optical power of the RSOA. However, it was saturated when the DMT signal had a peak-to-peak voltage higher than 4 V. Above this level, the undesired signal components such as 3^{rd} order intermodulation distortion products, which were generated from the nonlinear property of the RSOA, increased steeply compared to the DMT signal, and reduced the performance improvement.

The symbol rate of the DMT signal was 4.883 Msymbol/s in the case of 512 DMT subcarriers. Hence, the impact of chromatic dispersion was much smaller than that of the systems based on the electrical equalization techniques. Therefore, the cyclic prefix, which played a role of a buffer, was negligible to mitigate the dispersion effect as shown in Fig. 6 (d).

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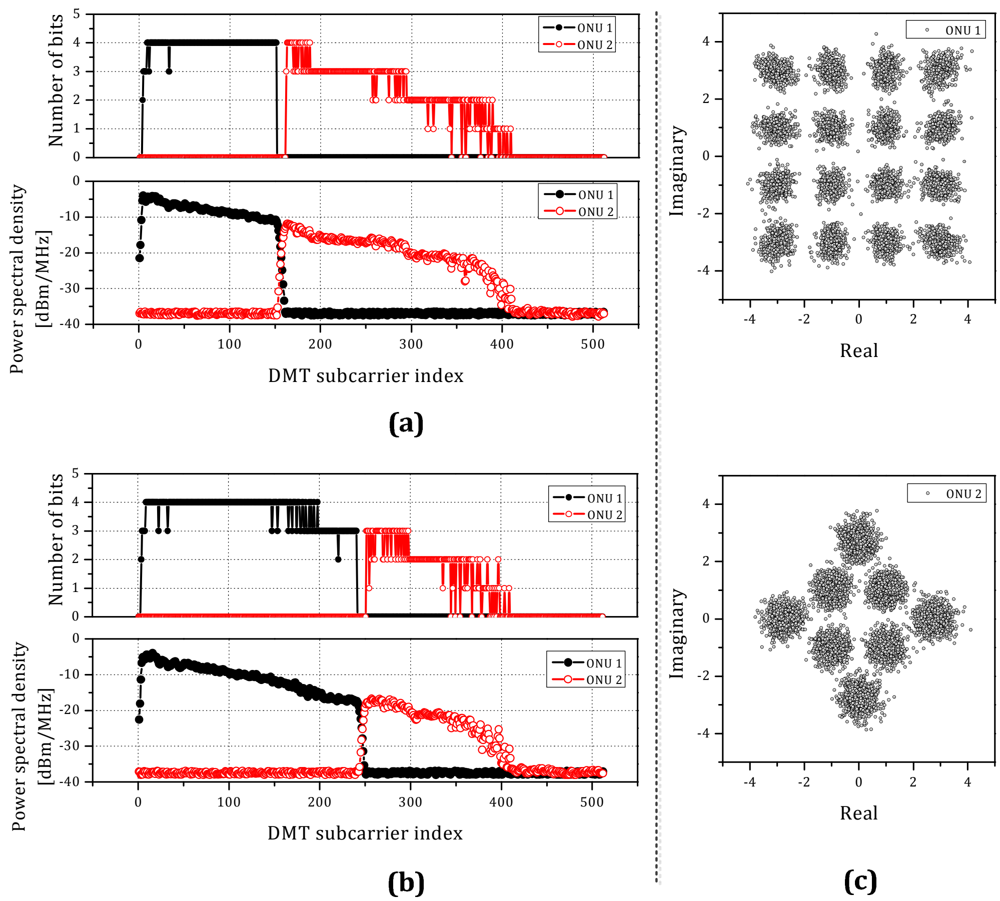

Fig. 7. Flexible bandwidth allocated multiple access measurements: bit-loading profiles and power spectral densities for (a) 50:50 (4.56:4.53Gbit/s) and (b) 75:25 (6.89:2.21Gbit/s) distribution scenario; (c) signal constellations for 50:50 allocation (top: ONU1-16QAM, bottom: ONU2-8QAM).

Multiple access was implemented by allocating the parallel-mapped data into a pre-determined number of DMT subcarriers. In addition, the data capacity provided for each ONU could be flexibly adjusted by modifying the number of occupied subcarriers per ONU. The number of DMT subcarriers for a certain ONU should be carefully selected even in the case of a 50:50 capacity distribution. It was caused by the asymmetric bit-loading profile among the entire set of DMT subcarriers. Nevertheless, it was possible to accomplish a flexible bandwidth allocation for multiple access operation by using the proposed scheme as illustrated in Fig. 7. We successfully demonstrated it for the 50:50 and 75:25 bandwidth-split. In this operation, 10 subcarriers (around 80 MHz width) were chosen as a guard band to prevent interference between the ONUs.

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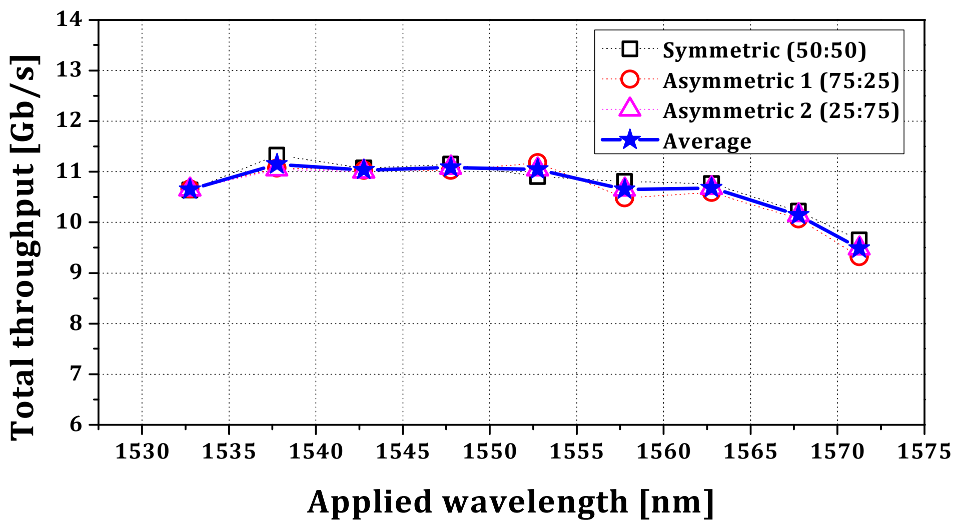

Fig. 8. Validation of the colorless operation in terms of maximum achievable total throughput via various bandwidth allocation scenarios (measured at the input optical power of the RSOA and the preamplifier, −10 dBm and −15 dBm, respectively).

Colorless operation of the proposed scheme was also validated in terms of total throughput as represented in Fig. 8. At the applied optical carrier wavelength from 1532.5 nm to 1567.5 nm, equivalent to almost the entire C band, the total throughput of 10 Gbit/s was consistently accomplished at the input optical RSOA and preamplifier power of −10 dBm and −15 dBm, respectively, regardless which bandwidth split the proposed scheme employed (symmetric and asymmetric). This throughput was slightly reduced at a wavelength beyond 1567.5 nm because those wavelengths lie at the edge of the preamplifier.

5. Conclusion

We successfully demonstrated that employing DMT, a remotely seeded 1-GHz RSOA at the ONU can be used for > 10 Gbit/s WDM PONs. The DMT technique using an adaptive bit and power-loading algorithm was employed to overcome the bandwidth limitation of the RSOA. The proof-of-concept experiment shows the feasibility of the flexible bandwidth allocated multiple access scheme for the case of two ONUs sharing the same wavelength. This concept also allows us to accommodate more than two ONUs. To the best of our knowledge, the proposed transmission link is the first multi-Gbit/s demonstration based on the realistic scenarios of a single fiber link with a remotely fed, commercially available 1-GHz RSOA, opening the possibility for multiple access. In addition, our recent experimental investigations indicate that, signal reflections can be minimized employing clipped DMT tones. Hence, the proposed scheme can demonstrate a maximum of 16-Gbit/s transmission over a 20-km single fiber link.

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